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ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF
LIQUID DOUBLE DROP DYNAMICS: PRELIMINARY DESIGN FOR
SPACE SHUTTLE EXPERIMENTS

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Final Report

UCSB NASA NAG 2-27

(NCC 2-11)

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ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF
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Summary

UCSB NASA Grant NAG 2-27 (\$23,943; April 1, 1980 - March 31, 1981) continues the research began under a preliminary grant, UCSB NASA NCC 2-11 "Investigation of Liquid Drop Dynamics in Zero Gravity", (\$14,951; May 1, 1979 - March 31, 1980). The current grant was continued on a no-cost extension through December 31, 1981. The preliminary grant assessed the use of laboratory experiments for simulating low-g liquid drop experiments in the space shuttle environment. Investigations were begun of appropriate immiscible liquid systems, design of experimental apparatus, and analyses. The current grant continued these topics, completed construction and preliminary testing of the experimental apparatus, and performed experiments on single and compound liquid drops. A continuing assessment of laboratory capabilities, and the interests of project personnel and available collaborators, led to, after consultations with NASA personnel, a research emphasis specializing on compound drops consisting of hollow plastic or elastic spheroids filled with liquids. Major laboratory deficiencies were encountered relative to laboratory space and an adequately large and accurate spin table. These deficiencies were resolved during the summer and fall of 1981 and several graduate students and a sabbatical visitor are currently using the facility on relevant research projects.

Report

The principal investigator was occupied on a sabbatical visit to Australia (CSIRO Division of Atmospheric Physics) during the final months of NCC 2-11 and the early months of NAG 2-27. Work started on NAG 2-27 during the summer of 1980 with assistance of an undergraduate Physics major. The rotating tank, designed for "Plateau type" experiments on suspended liquid globules and initiated during NCC 2-11, was completed. It was equipped with a miniature hydraulic control system for remote operation on a rotating table available from previous departmental research. In that ultimate experiments were to be designed for use in the space shuttle environment, where all such experiments are to be capable of remote and/or automated operation, a decision was made to achieve capability for automatic control of experiments in the laboratory.

The rotating tank is nominally 12" diameter by 22" high. The manipulator mechanisms increase its size to approximately 24" diameter by 34" high. The available rotating table was 24" diameter and was only marginally adequate in its ability to support and to spin the tank and accessories. In addition, a limitation on slip ring capability created considerable difficulties in achieving remote operation. A number of experiments were successfully completed using single drops of silicone in a water-methanol flotation solution. The drops were remotely injected, rotated, oscillated, and withdrawn. Manipulation included differential rotation and generation of classic principal modes of spherical oscillations. Compound drops were created, although not with the tank rotating, nor remotely. It became apparent that table size, stability, and slip ring capability were critical limitations relative to success with compound drop experiments. Bouyancy stability was achieved using flotation liquids with density gradients.

The physics Laboratory Assistant took a leave of absence from UCSB limiting progress during the early part of the 80-81 academic year. A mechanical engineering graduate student expressed interest in the project and had an adequate academic record. He was hired as a Research Assistant to continue the research. Unfortunately, his laboratory and experimental skills did not match his academic skills, and although he made progress in understanding the theoretical problem, he was not able to achieve further experimental successes. At about the same time a change in management made it possible to obtain much better laboratory facilities and nearly \$20,000 of general research funds to equip the new laboratory. These funds were spent on a new rotating table and on temperature controls for the flotation liquid. The new table was designed and ordered in the spring of 1981 and was delivered that September. It is five feet in diameter and is flat and spins true within about 0.003 inches total error. It also has extensive slip ring capability - both for conventional and coaxial channels. Its spin speed is accurately controllable to from approximately 0.10 rev/min to 100 rev/min.

The physics student returned, graduated, and worked again during the summer of 1981 as a Reserach Assistant. However he decided against a graduate program in September and accepted instead an industrial position. The Principal Investigator continued the research unassisted to its conclusion in December of 1981. Because of the difficulty in finding students with laboratory skills and the difficulty of maintaining continuity during possible student turnovers, it may be necessary to budget in the future for a full-time laboratory technician in addition to graduate student assistance. This will be especially true as research nears actual design and fabrication for space shuttle experiments.

During the summer of 1981, the physics Research Assistant implemented electromagnetic manipulators to augment the hydraulic actuators in anticipation of the new spin table. We also initiated the development of "compound drops" consisting of elastic and gelatin thick walled spheroidal shells filled with liquids. One application of this model is to simulate global geodynamics treating the earth as a thick walled spheroidal shell filled with a viscous liquid. Successful simulation requires ability to spin and precess the model while subjecting it to simulated solar and lunar gravitational forces and torques. Precession may be achievable by externally torquing an inertially nonspherical model or by simply precessing the entire rotating tank arrangement. Both capabilities are being developed. An additional intermediate spin table, with inclinable spin axis, has been designed to achieve precession capability and the commercial components have been purchased. The preliminary design and purchase of components occurred as part of NAG 2-27. Detail design has been completed since then and fabrication will be completed as a departmental research expense. One graduate student is currently completing this as an M.S. thesis project without financial support.

We initially created thick walled shells of vegetable and animal based gels by injecting the gels in the liquid mode into a flotation silicone liquid and then cooling the system to achieve an elastic gelatin form. We had limited success in injecting silicone into their interiors to form compound drops as the outer drop gelled. We also experimented with very soft (after curing) silicone elastic shells, also formed while suspended in a flotation liquid. The silicones during curing are extremely sensitive to the ph of the flotation liquid. We were never completely successful in casting such shells without the appearance of chemically formed gas bubbles

at the liquid-silicone surface. A second major difficulty in both cases is that of centering the liquid core accurately within the external surface of the shell. Before the Research Assistant left in September, we had completed preliminary designs for casting the thick walled spheroidal shells in rigid molds and with rigid internal cores to be later removed and replaced with a desired liquid. The process inevitably leaves at least minor imperfections in the elastic (or gelatin) silicone shell but refinements in the process appear to be possible. A significant advantage in the use of this type of compound drop is the obvious (relative) ease for experimenting with them in the space shuttle environment. A third graduate student is now completing the project of routinely manufacturing spherical and spheroidal liquid filled shells as an M.S. research thesis without financial support. This student has an interest and potential ability to continue the research through space shuttle experiments should funding be available.

The principal investigator published in September 1981 a paper, "A model for energy dissipation at the mantle-core boundary", Vanyo & Paltridge in the Geophysical Journal of the Royal Astronomical Society. This work was supported in part by NCC 2-11 and NAG 2-27 and details an analysis of possible interactions between the earth's liquid core and the earth's mantle as a result of forced precession caused by lunar and solar interactions. The integration of facilities initiated during these NASA grants and facilities developed earlier by the Principal Investigator to research energy dissipation rates and effective inertia tensors in precessing nonrigid systems is discussed in a preliminary proposal submitted to NASA personnel in Washington, D.C. in December 1981. Two students are completing M.S. thesis projects on this other facility. One is completing construction

and testing of the inertia tensor measurement capability and the other is performing an experiment to attempt to analyze performance anomalies of an existing U.S. satellite as an extension of a current contract with Ford Aerospace and Communications Corporation. Both the Geophysical Journal paper and the preliminary proposal are attached. Photographs of the experimental apparatus are included with the preliminary proposal.

Since last autumn the laboratory has had the services of a scientist/engineer who is spending a one year sabbatical at UCSB (Sept. 1981 - June 1982). He has helped set-up the large spin table and together we have designed and are presently testing a laser doppler velocimetry system integrated with the spin table. This includes a basic DISA LDV system available from earlier research and redesigned optics to facilitate use on the rotating table.

In addition to the Geophysics Journal paper several other papers on experimental technique and geodynamics are in preparation and will be forwarded to NASA when completed. A proposal anticipating funds to complete a geodynamics experiment aboard the space shuttle will be submitted to NASA in the near future.

A model for energy dissipation at the mantle–core boundary

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Summary. An existing experimentally verified model for energy dissipation in a precessing spherical cavity filled with liquid assumed to be in a semi-rigidized state except for a viscous Ekman boundary layer is applied to the Earth's liquid core to assess energy dissipation magnitudes. Application of the model to the best available Earth data occurs at the derived energy dissipation maximum for the model. Other existing research showing that the Earth's atmosphere appears to adjust to a state of maximum dissipation led to generic models for systems of maximum dissipation. The maximum dissipation mantle–core model with core motion driven by Earth precession alone, coupled to the mantle only by viscous shear stresses, and with a spherical mantle–core boundary leads to energy dissipation rates on the order of 10^6 times those necessary for an Earth dynamo. The maximum dissipation model also leads to excessive magnetic field drift rates and to excessive retardation of the Earth's rotation rate. Effects of the mantle–core ellipticity and of magnetic field coupling are briefly discussed and are used to help develop a less than maximum dissipation model also driven by precession alone but using the additional coupling to yield a model more consistent with observed phenomena.

Introduction

This research combines prior research of Vanyo & Likins (1972), Vanyo (1974) and Vanyo, Lu & Weyant (1975) that had been oriented to resolving a rotational instability problem encountered with communication and other satellites with prior research of Paltridge (1975, 1978, 1979) that had been oriented to global climatic dynamics and applies them to a model for the Earth's liquid core.

The work of Vanyo *et al.* had resulted in an analytically derived and experimentally verified model for liquids in a filled precessing spherical cavity. Energy dissipation within the liquid was computed using as a model a 'rigid sphere of liquid' separated from the cavity

wall by an Ekman layer of the (viscous) liquid. Relative torques, motions, and energy dissipation rates were related to the inertial resistance of the internal sphere to the precessional motion of the cavity.

The model was developed originally to help resolve design problems with rotationally stabilized communication satellites. For an inertially prolate satellite spinning about its long axis any internal energy dissipation occurred at the expense of the rotational kinetic energy of the vehicle driving the vehicle to its minimum energy configuration of spin about a transverse axis with consequent loss of use of solar energy panels and Earth directional antenna. Often the major energy loss was due to liquid fuels in spherical tanks. A laminar solution, obtained by integrating Stokes' solution for an oscillating flat plate over a spherical surface, was the then current analysis, and the rigid sphere solution was tried as an alternative. It yielded energy dissipation rates an order of magnitude or more greater than the solution then being used.

Both solutions were compared to a series of laboratory experiments for liquids in a precessing spherical cavity (5.5–22 cm diameter, half coning angles 1–30°, precession speeds up to 800 rpm, and spin speeds up to 1000 rpm). The rigid sphere model predicted actual energy dissipation rates within the liquid usually within several per cent. The model appeared to fail only at the extreme of very slow motions or very large viscosities (Stokes flow) and possibly also at the other extreme of net angular velocities on the order of 2000 rpm (large Reynolds – very small Ekman numbers).

The work of Paltridge had resulted in analyses of the Earth's global climate leading to a conclusion that the Earth's atmosphere had 'adopted' a net steady state format of maximum dissipation. This led to studies extending the concept of energy dissipation maxima to complex natural systems.

The rigid sphere model has a computable maximum for energy dissipation. When applied to best estimates of Earth core data it leads to a similar energy dissipation maximum. Additional aspects of this model and its relationship to known and estimated Earth phenomena are briefly discussed.

Dynamics of a semi-rigid sphere in a precessing spherical cavity

A complete solution is available for the dynamics and motion of a rigid sphere, interior to, but separated from a precessing spherical cavity by a layer of viscous fluid (Vanyo & Likins

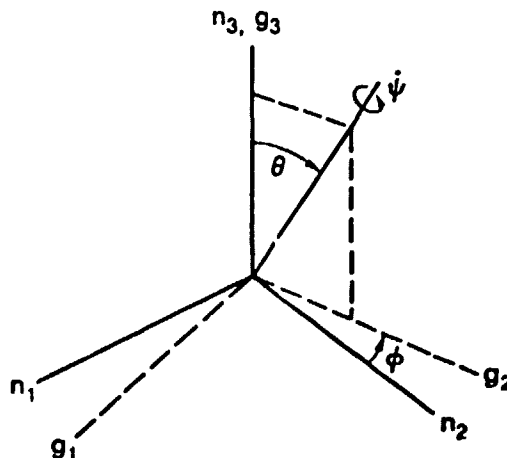


Figure 1. Coordinate system showing Euler angles.

1972). The cavity is assumed to be given an impulsive precessional motion of spin speed $\dot{\psi}$, whose axis is at an angle θ with the inertially fixed direction of the precessional axis. The precessional speed is $\dot{\phi}$. Both the transient and steady state three-dimensional motions of the rigid interior sphere are obtained given the density ρ of the sphere, its radius R , and the thickness h ($h < R$) and viscosity μ of the viscous fluid for the case of constant $\dot{\phi}$, $\dot{\psi}$, and θ .

In a frame designated the g frame in Fig. 1, the complete solution for the angular velocity of the sphere relative to the g frame (ω^{gs}) is:

$$\begin{aligned}\omega^{gs} = & -\frac{\xi}{1+\xi^2} [1 - (\cos \dot{\phi}t + \xi \sin \dot{\phi}t) \exp^{-\xi \dot{\phi}t}] \dot{\psi} \sin \theta \hat{g}_1 \\ & -\frac{\xi}{1+\xi^2} [\xi - (\xi \cos \dot{\phi}t - \sin \dot{\phi}t) \exp^{-\xi \dot{\phi}t}] \dot{\psi} \sin \theta \hat{g}_2 \\ & + (1 - \exp^{-\xi \dot{\phi}t}) \dot{\psi} \cos \theta \hat{g}_3\end{aligned}\quad (1)$$

with $\hat{g}_1, \hat{g}_2, \hat{g}_3$ being unit vectors along the respective g axes and with

$$\xi = \frac{5\mu}{\rho h R \dot{\phi}}. \quad (2)$$

The g frame is seen to be the frame rotating about the inertial frame n at rate $\dot{\phi}$ and with the \hat{g}_3 axis coincident with the inertially fixed \hat{n}_3 axis.

Energy dissipation due to viscous interaction is obtained from the work done on the interface fluid by the relative motion between the interior sphere and the cavity wall. In the steady state condition this is given by P (work per unit time, power):

$$P = \frac{\xi}{1+\xi^2} I \dot{\phi}^2 \sin^2 \theta \quad (3)$$

with I the moment of inertia of the sphere about a diameter.

It is evident that P has a maximum relative to ξ which occurs at $\xi = 1$. Note that equation (2) permits a multiplicity of values of μ and h that satisfy specific values of ξ subject only to the constraint $h < R$. Fig. 2 gives non-dimensional P [or $(\xi/(1+\xi^2))$] as a function of ξ .

The condition $\xi = 0$ is the limit of an inviscid interface fluid. The interior sphere is isolated from the cavity wall, moments on the sphere are zero, and of course $P = 0$. The condition $\xi = \infty$ is the case of a rigid coupling between the interior sphere and the cavity wall. Moments exerted on the sphere are at a maximum, but relative motion is zero and again $P = 0$. At P_{\max} , with $\xi = 1$, the rotation axis of the sphere lags a constant $\alpha = 45^\circ$ behind the $\hat{g}_2 \hat{g}_3$ plane and is at an angle of $\beta = \arctan(\tan \theta / \sqrt{2})$ with the \hat{g}_3 axis.

In applying the model to an actual liquid-filled spherical cavity an assumption had to be made that the liquid, except for a thin layer of depth h , is rigidized whether by inertial wave

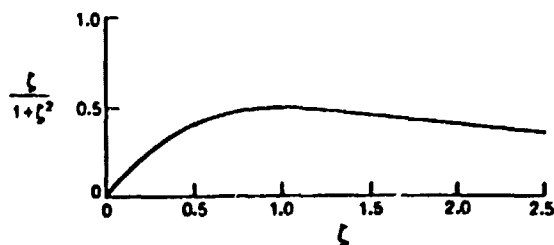


Figure 2. Dimensionless energy dissipation $\xi/(1+\xi^2)$ as a function of ξ .

interaction, by turbulence, or by some other means. Also some criteria were needed to select h . An obvious choice was to use an Ekman layer $\sim (\nu/\omega)^{1/2}$ with $\nu = \mu/\rho$ and ω a characteristic angular velocity. The constant was determined by equating an experimentally determined spin-up time for liquid filled gyroscopes (spherical cavity) determined by Wing (1963) to the derived time decay coefficient of the rigid sphere model ($\dot{\phi}$) yielding

$$h = \sqrt{2} \left(\frac{\nu}{\omega_s} \right)^{1/2}. \quad (4)$$

Here ω_s , the secular component of the cavity's precessional motion ($\dot{\phi} + \dot{\psi} \cos \theta$), is used as the characteristic angular velocity. The use of ω_s as the characteristic angular velocity was based on trial and error fits of several angular velocities (e.g. $\dot{\psi}$, or $\dot{\phi}$, or $|\omega^{se}|$, etc) to best fit the model to the experimental data. Another combination ($\omega_t = \dot{\psi} \sin \theta$) is the transient component of the cavity's precessional motion and appears naturally in equations (1) and (3). Both ω_s and ω_t appear in a later transformation.

Over a period of about eight years roughly 10 000 data sets were obtained with other tank sizes and viscosities. A transformation was developed that transformed the seven variable experimental space $f(P, R, \rho, \nu, \theta, \dot{\phi}, \dot{\psi}) = 0$ to a two-parameter analytical space $f(p, \xi) = 0$. Equation (3) after use of the transformation reduces to

$$\log p = \frac{1}{2} \log \xi \quad (5)$$

where $\xi = \nu/R^2\omega_s$ and $p = (1 + \xi^2)P/(\sqrt{2}MR^2\omega_t^2\omega_s)$ with M = enclosed liquid mass.

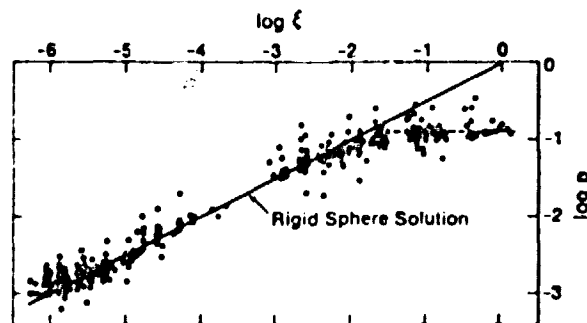


Figure 3. Experimental results for dimensionless energy dissipation as a function of Ekman number ξ (see Vanyo *et al.* 1975).

The summarized data and the rigid sphere model are shown in Fig. 3 taken from Vanyo *et al.* (1975). For details of the transformation see Vanyo (1974). The horizontal region at the right side of Fig. 3 includes a best fit line at about $\log p = -0.90$. A solution by Busse for energy dissipation based upon earlier analyses of liquid motion in precessing spherical cavities by Busse (1968) and Roberts & Stewartson (1965) yielded

$$P = \frac{2}{175} MR^4 \nu^{-1} \dot{\phi}^2 \omega_t^2 \quad (6)$$

for the region equivalent to Stokes flow ($\nu/R^2\dot{\phi} \gg 1$, $\nu/R^2\dot{\psi} \gg 1$). This is the region comparable to the right side of Fig. 3. Equation (6) after use of the transformation yields simply $\log p = -1.0$, quite close to the experimental value of -0.90 considering experimental errors in this difficult region of experiments and the approximations necessary to reach the theoretical solution. Data at the left of Fig. 3 appear to be reaching a limit at $\log p = -3$

although the apparent limit might be caused by experimental limitations rather than by a change in a basic flow phenomena. Use of the transformation in reverse at that value of p gives

$$P = (\sqrt{2} \times 10^{-3}) MR^3 \omega_1 \omega_2^2. \quad (7)$$

Note that viscosity does not appear in equation (7) which is consistent with motions characterized as having a turbulent boundary layer ($\xi \sim (1/R_0) < 10^{-5} - 10^{-6}$).

A tentative explanation has been advanced that the region $\log p = -1$ is dominated by viscosity throughout the interior and includes resonant motions as $\log \xi$ approaches -2 . Between $\log \xi = -2$ and -6 the interior liquid is semi-rigidized by a state of 'saturated' turbulence or inertial wave structures but with an Ekman boundary layer dominated by viscosity. At or beyond $\log \xi = -6$, a region is reached where the Ekman boundary layer degenerates into a boundary layer dominated by inertial phenomena rather than by viscous phenomena. There is a clear similarity between these three states for flow in a spherical cavity driven by inertial resistance of the fluid to precessional motion and the equivalent three states for flow in a circular pipe driven by an external pressure gradient.

In the 10000 energy dissipation experiments to date the motion of a liquid (water or silicone fluids of 20, 10³, 10⁴, and 6×10^4 cs) in spherical cavities (22, 16.5, and 11 cm diameter) precessing at $1^\circ < \theta < 30^\circ$, $7.5 < \psi < 1000$ rpm, and $1 < \phi < 800$ rpm usually yielded energy dissipation rates accurately modelled by use of equation (3). It led the researchers to believe that some process, possibly turbulence, possibly inertial waves, or a combination, did often effectively rigidize the internal liquid except for a thin Ekman layer.

Energy dissipation rates not modelled by the 'rigid sphere' equation (3) typically occurred at experimental extremes. Some at very slow speeds or with very large viscosities, e.g. results with $\nu = 6 \times 10^4$ cs, comprise the horizontal set at the right side of Fig. 3 and fit the predictions of equation (5). This region also included some of the data points using the 10⁴ cs liquid. All the data points modelled by equation (7) at the lower left of Fig. 3 were obtained using water in the 22 cm diameter cavity at $\dot{\psi} \sim 900$ rpm, $\dot{\phi} \sim 600$ rpm, and θ at 20° and 30°. At these speeds gyroscopic moments within the apparatus caused several failures. The conclusion is that rigid sphere results are easy to attain, at least in the laboratory; the others are difficult to obtain. Liquid motions in spherical and nearly spherical precessing cavities that yield energy dissipation rates modelled by the rigid interior sphere model should be regarded as a natural and common occurrence.

Application of the rigid sphere model to the Earth's liquid core

All models developed to represent motions within, and dynamics of, the Earth's liquid core are speculative in various degrees, and it is useful to examine any reasonable model both for its own merit as a potential real solution and for the potential of setting limits on possible solutions.

The hard data must be met. These include that the interior inside the mantle-core boundary (MCB) cannot transmit shear waves and is therefore a liquid or an adequately 'soft' plastic substance, that the MCB mean radius is very near to 3.48×10^3 km, that the enclosed mass is about 1.94×10^{24} kg (about 1/3 of the Earth's mass) and even that $\rho(r)$ is adequately known (e.g. Jordan & Anderson 1974). Further, the kinematics and dynamics of the Earth's surface and the Earth-Sun-Moon system are accurately known as are the properties and to some extent the history of the external magnetic field (e.g. Marsden & Cameron 1966; Munk & MacDonald 1975; Jacobs 1975; Brosche & Sündermann 1978).

Other data, although based on considerable inference, are yet plausible enough to use

with caution. Certainly any model in disagreement with these other data would need to address the discrepancy. These include that the MCB most likely has an oblate ellipsoidal shape with ellipticity around 1/400 but possibly with irregularities on the order of 1 km in size (see Hide 1969, Jacobs 1972, and McElhinny 1978). Further, the temperature is in the vicinity of 3500–5000 K (Verhoogen 1973), and at these temperatures the material is a plasma relative to its ability to interact with magnetic fields. Although based on more inferential data and analysis the value of $6 \times 10^{-3} \text{ cm}^2 \text{ s}^{-1}$ has generally been accepted as the kinematic viscosity of liquid at the MCB (Gans 1972). In addition estimates of required energy production to offset ohmic dissipation in any dynamo field model ($\sim 10^{19} \text{ erg s}^{-1}$) and to provide thermal outflow fluxes ($\sim 2.5 \times 10^{20} \text{ erg s}^{-1}$) and earthquake and tidal energies, etc. (Munk & MacDonald 1975) have been made. Failure to provide adequate energies has been a major flaw in existing models.

All other statements regarding motions within the core and the origin and maintenance of magnetic fields involve some speculation. Dynamo models have as a group been criticized as first needing to postulate motions in the core. It is certainly speculative to assume that anomalies in the external field can be attributed in any simple way to core motions, especially when the mantle near the MCB has essentially the same temperature as the liquid and may have very similar electrical properties. Further, to assume that the net MCB maintains an adequately smooth surface to ensure the constancy of its ellipsoidal shape may be incautious. The difference between the equatorial radius and the polar radius would be roughly 8 km; stated irregularities of $\pm 1 \text{ km}$ probably come from a family of irregularities up to say $\pm 3 \text{ km}$. Also materials and conditions on both sides of the MCB must often be very similar so that any internal disturbances could roll-off or erode the surface material to the order of 8 km.

It is not unreasonable within the above possibilities to test the potential for an earth core model that assumes the limiting case of a spherical cavity. We investigate the effect of applying the models given earlier for energy dissipation caused by liquids in a precessing spherical cavity to the liquid core of the Earth assuming a nearly spherical MCB shape. Incidentally 1 km in 3470 km is the same percentage roughness as 0.003 cm (or 0.0013") in 11 cm. The 11 cm radius cavity used for most of the referenced tests was machined 12 years ago from cast epoxy to an expected tolerance and smoothness of ± 0.002 ". The difference in semi-major and semi-minor axes of the MCB ellipsoid of 8 km is the same percentage as 0.025 cm (or 0.010") in 11 cm. The machined spherical cavity has been carefully remeasured and is currently about 0.005" out of round at its spin axis equator, and its radius in the spin axis direction is about 0.010" greater than the average equatorial radius. At rest the cavity is slightly prolate $(a - b)/a \sim 1/400$. When filled with liquid and spinning at typical spin speeds internal forces will tend to distort the cavity more nearly to a spherical shape. In any event it may be that the real experimental cavity and the real MCB are geometrically quite similar in surface roughness and out-of-round.

We consider the case of forced precession of the Earth with a precession rate of $-7.71 \times 10^{-12} \text{ rad s}^{-1}$ (25 800 yr period), a spin rate of $7.29 \times 10^{-5} \text{ rad s}^{-1}$ (sidereal day), a half coning angle of 0.41 rad ($23\frac{1}{2}^\circ$), and ρ , ν , and R given above. These values of $(R, \rho, \nu, \theta, \phi, \psi)$ when used in equations (4), (2), (5) and (3) yield

$$h = 13.4 \text{ cm},$$

$$\xi = 0.837,$$

$$\xi = 7.45 \times 10^{-16},$$

$$P_t = 3.53 \times 10^{23} \text{ erg s}^{-1}.$$

where the subscript r indicates a value computed by the rigid sphere model. The value of h for the Ekman layer thickness is consistent with computations performed by others although its application to a surface with possible irregularities of 1 km or so needs careful attention. The value of $\log \xi \approx -15$ places it well to the left of the laboratory results shown in Fig. 3. Use of equation (7) of the relatively unverified 'turbulent boundary layer' model would yield an energy dissipation rate of about $2 \times 10^{28} \text{ erg s}^{-1}$. Use of the more conservative rigid sphere with 'laminar boundary layer' yields the P_r shown.

The value of $P_r = 3.53 \times 10^{23}$ is much greater than the estimates of up to $10^{19} \text{ erg s}^{-1}$ required for ohmic dissipation of a dynamo model (Rochester *et al.* 1975). The effect of these energy dissipation rates on the long-term angular velocities of the mantle and core is discussed briefly in the next section. Of considerable interest to this paper is the value of $\xi = 0.837$ and its very close proximity to $\xi = 1$ which is that value of ξ that yields an energy dissipation maximum for the rigid sphere analytical model. This apparent coincidence of ξ so near to the value of one is also discussed in more detail in the next section.

In the remainder of this section we discuss other implications of a rigid sphere model for the Earth's liquid core. We wish to caution that the 'rigid sphere model' does not imply a crystalline rigidity of the liquid core but only some fluid property or phenomena adequate to insure that the net motion of the liquid approximates the net motion that a genuinely rigid sphere would have. The rigid sphere model as used here applies as one unit to both the liquid outer portion of the core and the very much smaller central portion of the core generally accepted as composed of a solid elastic material.

Having computed a value of ξ , it is possible to compute the net motion of the rotating Earth core relative to the Earth mantle. Use of equation (1), after eliminating the transients, yields the components of the angular velocity vector of a rigid interior sphere relative to its precessing cavity. Using earth data one obtains the vectors shown in Fig. 4.

The rigid interior sphere analytical model at $\xi = 1$ and P_{\max} had ω^{sc} lagging the precession rate of $\dot{\phi}$ by a fixed 45° . Application to the Earth core data with $\xi = 0.837$ yields a lag angle of 40° or, as viewed from the Earth, lagging at 39° from the plane of the polar and

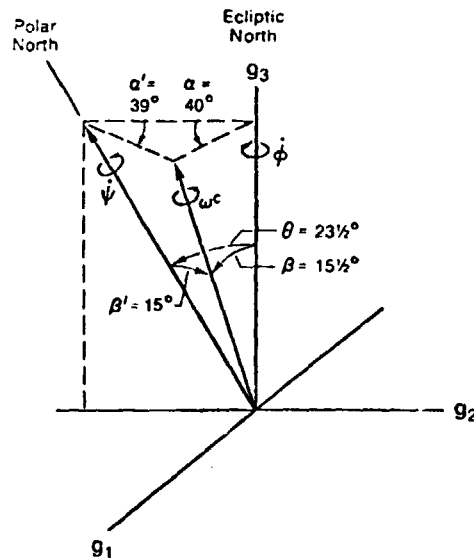


Figure 4. Relative positions of angular velocities of the mantle ($\dot{\psi}$) and the core (ω^c) in the rigid sphere model with viscous coupling.

ecliptic axes. The angle β for $\xi = 1$ would be $\arctan(\tan \theta/\sqrt{2})$ or 17° . With $\xi = 0.837$ the value of β is $15\frac{1}{2}^\circ$ or, as the angle measured from the polar axis, $\beta' = 15^\circ$. Note that the angular relationships are constant relative to the precessing g frame (period of 25 800 yr) as are the magnitudes of the angular velocities. The magnitude of ω^m is $0.952 \omega^{ms}$ where ω^{ms} is the magnitude of the angular velocity of the mantle relative to the precessing g frame. The period of the core is approximately 25h 13m.

The mantle slips over the poles of the core (per this model) once per day and at latitudes of $\pm 75^\circ$ respectively. Near the equator the difference in angular velocities of the core and mantle causes a drift rate of about $17^\circ \text{ day}^{-1}$ with the core moving westward relative to the Earth's surface. The equivalent shear velocity of the MCB would be about 21.5 km h^{-1} . This rate is considerably faster than the observed westward drift rate of anomalies in the Earth's surface magnetic field of about 0.2 to $0.3^\circ \text{ yr}^{-1}$ (Dodson 1979). One should expect a larger drift rate for a field locked into the core than is observed at the surface due to restraints on the motion of any field structure through a conducting lower mantle, also of course magnetic or other coupling effects between the core and mantle would further reduce the drift rate. Additional coupling would also tend to force the core axis to align more closely with the geographic (ψ) axis, for example nearing the observed $\pm 79^\circ$ latitude of the surface magnetic pole locations. The amount of additional coupling needed to match the rigid sphere model of the core more closely to observed Earth phenomena is estimated in the last section.

Systems stationary at energy dissipation maxima

The idea that certain non-linear systems may be constrained to a format of maximum dissipation is not new, but no formal or general development of the concept exists to date. A semi-quantitative basis for this idea was suggested recently (Paltridge 1979) with reference to the Earth-atmosphere climate system. In this case available data and analysis tend to confirm that the Earth-atmosphere system has 'adopted' a steady state of energy dissipation maxima.

Specifically, the climate system is such that there is a net input of radiant energy at the higher temperatures of the equatorial regions, and a balancing net output of radiant energy at the lower temperatures towards the poles. There is therefore a poleward meridional flux X of energy in the atmosphere and ocean which in the thermodynamic sense is being 'degraded' to lower temperatures. The measure of the rate of degradation is the rate of entropy production \dot{S} which can be defined at any latitude as

$$(\dot{S})_\lambda = \frac{XdT}{T^2} \quad (8)$$

Here T is the temperature, dT is the latitudinal temperature change, and all of X , T and dT are the specific values at latitude λ . The corresponding measure in terms of the rate of dissipation D is given by

$$D_\lambda = \frac{XdT}{T} \quad (9)$$

The total of entropy production \dot{S}_i or dissipation D are simply integrals over all latitudes.

Since in steady state the total entropy S must be constant (S is a macroscopic extensive property of the system) the internal production rate \dot{S}_i must be balanced by a net outward flow \dot{S}_0 associated with the radiant energy input and output E_r . That is

$$\dot{S}_i = -\dot{S}_0 = \int \frac{E_i}{T} d\lambda \quad (10)$$

where E_r is the net radiant energy *input* to the top of the atmosphere at each latitude. (E_r is positive toward the equator and negative toward the poles, and the overall integral is in fact negative because of the energy balance constraint in steady state that $\int E_r = 0$.)

Paltridge (1975, 1978) set up a model of the Earth-atmosphere climate system which (apart from the fixed input parameters defining the physical characteristics of the system) was constrained only by the requirements of energy balance and steady state. These requirements allowed calculation for all regions of the globe of the cloud cover, temperature and etc., and hence of E_r , once the distribution of horizontal energy flux X was arbitrarily defined. It was found that there was a unique distribution of X which led to a maximum of \dot{S}_i defined via equation 10 (i.e. a mathematical minimum in the negative quantity \dot{S}_0). Further, this unique distribution was associated with a format of cloud cover, of temperature, of E_r and of X itself which corresponded very closely to the observed format of the real world. The implication was that the Earth-atmosphere system has selected that steady state (from the set of possible steady states — see later) of maximum rate of entropy production or of thermodynamic dissipation.

The physical reason for such selection by complex non-linear systems was discussed in the 1979 paper. At this stage it should be pointed out that there is no incompatibility of this result with the more generally known concept of *minimum* dissipation developed by Prigogine (1967). His concept concerns linear systems whose fixed boundary conditions ensure the possibility of only a single steady state. That state has minimum dissipation when compared with perturbed (i.e. non-steady-state) conditions of the system.

In the present context the concern is with a much wider, and entirely different, set of non-linear systems in which internal feedback to the boundary conditions allows a number of possible steady states — none of which incidentally are necessarily a local minimum of dissipation as far as small perturbations are concerned. In the 1979 paper it was pointed out that a qualitative set of conditions required for a complex system to be constrained by a maximum dissipation principle are as follows:

- (1) that the system is non-linear overall in that feedback to a major energy source (input) allows the existence of a number of possible steady states;
- (2) that it is subject to internal random fluctuations which are on occasion large enough to boost the system from one stable steady state to another; and
- (3) that it has an internal non-linearity such that the random fluctuations preferentially displace the system toward the steady state having higher dissipation.

Many natural phenomena can reasonably be expected to fulfill these conditions. However a particular difficulty with natural phenomena is that it is generally extremely difficult to prove that steady states in addition to the observed steady states are physically allowable by the dynamic or other restraints on the system. The Earth-atmosphere is a classic example. Even though the physical phenomena are nominally accessible to observation, complexity of the physics and modelling of the system both exceed capability for rigorous proof.

The Earth-core system will presumably remain inaccessible to direct observation. However this lack of direct observation has promoted rather than impeded development of alternative steady state models. A constraint as suggested above predicting the possible existence of energy dissipation maxima in complex natural systems provides a potential basis for selecting from a number of alternate models of proposed steady state conditions that model most likely to represent reality. Further, it can be used to set boundaries on permissible models.

The Earth-core system appears to fit well the criteria stated above for systems capable of achieving energy dissipation maxima. First it is a complex system consisting of the

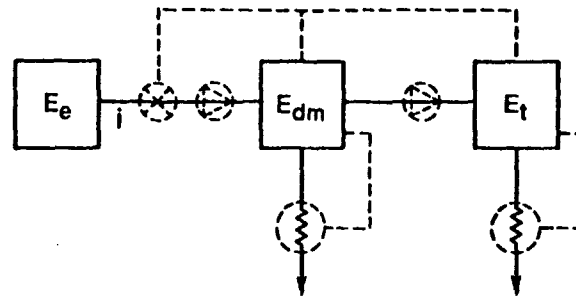


Figure 5. The total Earth mantle-core system of: energy transfers (solid lines); reservoirs of stored energy as available energy of mantle-Sun-Moon (E_e); net differential motion and magnetic field energy (E_{dm}); and turbulent motion energy (E_t); dissipation to thermal energy (resistor symbols); feedback to the rate at which energies are used and dissipated (dashed lines); and an indication of the non-linearity of the rate of energy conversion (diode symbols).

rotating oblate earth forced into precession by solar and lunar interactions with residue rotational kinetic energy of the system being the energy source.

Fig. 5 shows a schematic of the energy system as analysed here. E_e is the available energy residue from the Earth-Moon-Sun system (especially rotational kinetic energy of the mantle), which supplies the basic flux of input energy i . By viscous (or other) coupling this energy is imparted to net rotation of the core which because of forced precession must be at a net different rate and direction than the rigid mantle. Rotational kinetic energy of the present Earth is approximately 2×10^5 times the yearly dissipation rate computed for P_t . This very large rate of rotational energy loss indicates a further need for additional coupling mechanisms at the MCB.

Any established differential rotation between the core and mantle provides a major intermediate energy storage mechanism of particular interest in analysing applications of the rigid sphere model to the Earth mantle-core problem. Steady state differential rotation for the Earth mantle-core model of Section 2 possesses energy on an order adequate to supply estimated ohmic dissipation rates for 400 yr. E_{dm} represents energy stored as net differential rotation of the core and in magnetic field structure E_t is energy temporarily stored in turbulent motions.

Stored kinetic energy dissipated to thermal energy occurs in the Ekman layer and in ohmic dissipation from the block labelled E_{dm} and in viscous decay of turbulence from the block labelled E_t . The figure is similar to fig. 1 of Paltridge (1979) that originally presented the concept based on the Earth-atmosphere system. Numerical estimates for the Earth-atmosphere system can be found in that and preceding references.

The existence of alternate steady states (within appropriate time-scales) can be hypothesized but not proven as noted above — although some might be shown to be feasible within available analysis and data. The necessary feedback mechanism for modulating the flow of source energy in this model are the coupling mechanisms between the mantle and the core. If, for example, the Earth were rigid throughout (maximum coupling) then no internal relative motion could occur; no energy would flow from the external system to the core; and energy dissipation caused by mantle-core interactions would take the minimum value of zero. At the other extreme a core completely uncoupled from the mantle has maximum velocity relative to the mantle, but no torques, and again no energy dissipation. Neither extreme is physically realizable, but steady states near these limits are feasible as presumably would be a spectrum of intermediate states.

Viscous coupling between the mantle and the core provides the energy transfer mechanism of interest in this discussion, and dissipation within the liquid of the core provides

the thermal sink. Even neglecting coupling of magnetic effects or slight departures from sphericity, the non-linear viscous coupling mechanism provides a significant feedback between the rotating core and rotating mantle energy source. Variations in coupling in the model show up as changes in the parameter $\zeta = 5\nu/hR\dot{\phi}$, especially as changes in ν and h . Here relatively small variations can be responsible for significant changes in coupling and consequent energy flow.

Variations in coupling mechanism between the Earth mantle and Earth core obviously include changes in magnetic field structure and MCB temperature changes, such as would change the electrical conductivity of the material and/or the viscosity of the liquid. Other less provable variations are changes in inertial wave phenomena, turbulence and/or fluid motions within the core, and composition gradients. Non-sphericities including 'bumps' on the MCB induce turbulence whereas magnetic field structures would tend to suppress it. Viscosity plays a dual role. All effects are non-linear and are represented as such on Fig. 5 by the dashed diodes — although it hardly seems necessary to argue for non-linearity in that non-linearity has been a major obstacle in attempts to analyse nearly all mantle-core dynamo models.

External magnetic field strength and direction are directly observable and are known to include random components. Earth rotation rates also include randomities on a scale potentially adequate for the fluctuations necessary to pass from one steady state through a region of instability to an adjacent stable state. Known geophysical events in prior epochs, e.g. continental drift and major ice ages, would have provided major fluctuations.

It should be noted that ζ need not equal 1 in a precessing liquid-filled sphere in the laboratory. The laboratory experiments to date have yielded values of ζ from 14 to 10^{-4} although values of $\zeta = 1$ are achievable at many preselected conditions. The distinction between natural phenomena such as the mantle-core system capable of achieving $\zeta \sim 1$ and the laboratory experiments with preselectable value of ζ are that in the laboratory experiments feedback is carefully avoided and great care is exercised to eliminate fluctuations thus eliminating two features necessary for the dissipation maxima phenomena.

Discussion and conclusion

The Earth mantle-core system possesses a complex magnetic field structure that, as normally modelled, would provide additional coupling between the mantle and the core. No attempt is made in this paper to address the specifics of the magnetic field structure, or the possibility that a flow, modelled as a nearly rigid sphere and spinning at an oblique angle inside the mantle, can produce and maintain an Earth dynamo.

The effects of slight ellipticity have been analysed, especially by Busse (1968), but experimental work has not followed except for cases of moderate ellipticity and for cylinders. Malkus (1968) has published results of a limited experimental sequence of motions and energy dissipation in a precessing ellipsoid having an ellipticity of 1/25. McEwan (1969, 1970) and R. F. Gans (1970) have discussed results obtained with liquid-filled cylinders. W. C. Gans (1973) using the energy dissipation apparatus developed by Vanyo completed an experimental thesis programme of measuring energy dissipation rates in liquid-filled cylinders over a wide range of parameters. These results with cylinders and ellipsoids with moderate ellipticity indicate dissipation rates not describable by the rigid sphere model. However no specific and precise data exist for ellipticities near those of the MCB ($\sim 1/400$). Ellipticities less than 1/50 may be within the feasible range of laboratory experiments. Precise tests with ellipticities of say 1/50 or smaller would help to assess the relative importance of small deviations from sphericity.

The work of Busse indicates that ellipticities as small as $1/400$ may be significant, but it is difficult to apply such statements with confidence to a system as complex as the Earth core problem. McEwan for example has shown the great difficulty of creating inertial wave phenomena over a range of experimental parameters and the ease with which turbulent phenomena can frustrate the efforts. Given the possibility of turbulent conditions in the core it may be that existing analyses for non-turbulent flows only present limiting cases of the Earth-core problem and alternate methods need further consideration.

Indeed the matter of creation and maintenance of turbulence, with or without a magnetic field, may be of primary importance in assessing the validity of any fluid model or any dynamo model of the mantle-core system. Adequate models for meteorological and for engineering flows that possess detailed information on the onset of turbulence due to interior flow instabilities or due to growth of turbulence at boundary 'rough' spots are still in the formative stage. Corresponding problems exist with predicting flow conditions in the Earth's core. These are made even more complex by the great volumetric size of the core. Even the Earth-atmosphere problem may be simpler in that atmospheric effects occur in a layer some 2 orders of magnitude thinner than the core, in a layer that for many purposes can be analysed as a flat horizontal surface, and under conditions where the fluid portion cannot perturb the solid portions over most time scales of interest. A (near) sphere of liquid some 7000 km in diameter in a cavity whose inner surface has the same temperature and perhaps nearly the same density and composition in places can certainly exceed the complexities of atmospheric or engineering flow problems.

Scalar models of the mantle-core interaction problem have been published and criticized, many in the books and papers referenced here. The scalar approximations have been shown to be inadequate for a variety of reasons, e.g. moments are along an incorrect axis, drift rates are in the reverse direction, energy estimates are inadequate, etc. Often a net motion of the interior is either implicitly or explicitly assumed, rather than being derived as part of a solution. This vector solution appears to avoid the major problems of the scalar approximations with excessive energy dissipation rates caused by viscous coupling alone in a smooth spherical cavity result.

Yet the evidence of the vector rigid sphere solution and the laboratory results do indicate that the Earth mantle-core system, if the MCB were a smooth sphere, there were no magnetic field, and given the radius, viscosity, and densities as used would indeed behave as indicated here. As such, the dissipation maximum model is a useful limiting case. It also possesses an adequately large range of energy dissipation rates as a basis for explaining sudden and large deviations in earth rotation rate based on relatively small changes in coupling at the MCB.

It is possible to vary viscosity and/or other coupling phenomena so that the Earth core 'rigid sphere' model applies precisely to known geophysical data. The maximum dissipation rigid sphere model leads to energy dissipation rates $\sim 3 \times 10^{23} \text{ erg s}^{-1}$ compared to the 10^{19} estimated for Earth dynamo needs. The model drift rate between the core and the mantle is $17^\circ \text{ day}^{-1}$ compared to estimates of actual magnetic field drift rates of about $0.2^\circ \text{ yr}^{-1}$. A reviewer notes that both are off by nearly the same factor, i.e. 3×10^4 . The same factor would increase the estimate of $2 \times 10^5 \text{ yr}$ (for the ratio of Earth rotational kinetic energy to computed P_r) to something on the order of $5 \times 10^9 \text{ yr}$.

Fig. 2 and equation (3) indicate reduced energy by either increasing or decreasing ξ . Decreasing ξ indicates less coupling; increasing it indicates more. A decrease of dimensionless energy dissipation, $\xi/(1 + \xi^2)$, by a factor of 100 yields $\xi = 5 \times 10^{-3}$ and $\xi = 203$. Accepting constant values of ρ , R , and ϕ in (2) permits only μ/h to vary. Equation (4) shows μ/h proportional to $\mu^{1/2}$. At $\xi = 5 \times 10^{-3}$ this leads to $\mu \sim 1.2 \times 10^{-4} \text{ cp}$, a value typical of many gases. At $\xi = 203$ the necessary value of μ is $2 \times 10^5 \text{ cp}$, something like a soft tar (glucose at

85°C). Values appropriate to energy reductions of 10^{-2} , 10^{-3} , 10^{-4} are compared to those of the energy dissipation maximum model in Table 1.

Values of (α', β') are estimates for the angles shown in Fig. 4, with α' being the angle between the Earth polar axis and the axis of a 'rigid sphere' Earth core. The 'equat. drift rate' is the relative drift between the mantle and the core. All are westward drift rates. The parameter ' τ (diff. rot.)' is the ratio of energy stored in mantle-core differential rotation to the energy required for ohmic dissipation of an Earth dynamo (10^{19} erg s $^{-1}$). The parameter ' τ (tot. K.E.)' is the ratio of present total rotational kinetic energy of the Earth to the computed value of P_r for each case.

Table 1.

	'P _{max} ' model	$\times 10^{-2}$	$\times 10^{-3}$	$\times 10^{-4}$
P_r ergs/sec	3.53×10^{21}	3.53×10^{21}	3.53×10^{20}	3.53×10^{19}
h meters	0.134	32.8	330	3300
v cs	0.6	3.6×10^4	3.5×10^4	3.5×10^4
μ cp	3.33	2×10^5	2×10^7	2×10^9
ξ	0.837	204	2033	2.03×10^4
ξ	7.45×10^{-16}	4.5×10^{-11}	4.4×10^{-9}	4.4×10^{-7}
(α', β')	(39°, 15°)	(~90°, 0.1°)	(90°, 0.01°)	(90°, 0.001°)
equat. drift rate	17°/day	160°/yr	1.6°/yr	0.016°/yr
τ (diff. rot.)	400 yr	6 days	1.5 hrs	1 min
τ (tot. K. E.) yr	2×10^4	2×10^7	2×10^8	2×10^9

Coupling, equivalent to the viscous coupling, somewhere between the last two columns appears to be adequate to resolve nearly all the discrepancies noted earlier. Further, the changed value of ξ places the data point almost on the log p versus log ξ region of Fig. 3, and therefore may be a point attainable in the laboratory. The value of h in the last column is approximately 3.3 km, still $\ll R$ and not unreasonable relative to estimated MCB topography. The value $\mu \approx 2 \times 10^9$ is quite high, and the drift rate of $0.016^\circ \text{ yr}^{-1}$ too low. Of course if magnetic or other non-viscous coupling shares the necessary stresses then μ and h can be reduced without affecting P_r or other estimates.

A better overall fit may be given by values nearer the column headed by $\times 10^{-3}$ which also permits a drift rate slightly larger than observed surface magnetic drift rates. At all values of $\xi > 1$ the core axis nearly aligns with the mantle axis. For $\xi = 2033$ the energy stored in differential rotation can maintain ohmic dissipation for only about 1.5 hr. Earth rotational energy at $\xi = 2033$ is approximately 2×10^8 times the yearly rate for P_r with P_r now adequate for most estimates of total geophysical energy needs.

Chandler wobble (free precession) can also be analysed by the same method. Here the coning angle is much less than the $23\frac{1}{2}^\circ$ of forced precession, and the oblate Earth dictates a spin period (ψ) of 14 month retrograde to the precession period (ϕ) of 1 day. These parameters are sufficiently different than those of forced precession that the often implied convention of uncoupling forced and free precession phenomena is usually followed. The potential for interaction between forced and free precession as a mechanism for exciting the Chandler wobble is deferred to a separate study.

The purpose of this paper has been to present an application of a model for fluid flow in a precessing spherical cavity to the Earth mantle-core system, to compare it with a preliminary model for systems stable at energy dissipation maxima, and to assess the magnitude of additional coupling phenomena necessary to move the model into closer agreement with current estimates of geophysical data. Although the rigid sphere model precisely fits an

extensive range of laboratory experiments, its application to a system considerably more complex and 3×10^7 times larger in size leaves many questions unanswered.

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Global Earth Structure and Mantle-Core Dynamics

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RESEARCH OBJECTIVE

There currently exist several possible mechanisms for producing motions in the earth's liquid core and mantle and for regulating mantle-core interactions. Use of the earth's forced precession and to a lesser extent its free precession (Chandler wobble) have on various prior occasions been proposed by some and rejected by others. Analyses to prove or to disprove the arguments have been based on idealized models and have had to be applied to "fact" situations where the "facts" were usually as much in question as the basic model.

A recent paper by Vanyo and Paltridge¹ readdressed the use of forced precession as a mechanism for inciting motions in the liquid core and the use of relative motion at the mantle-core boundary as the source of necessary energy for maintenance of a geodynamo, for thermal surface outflow, for volcanism, etc. The Vanyo/Paltridge model relied on laboratory experiments and analyses originally developed to better understand attitude stability of earth orbiting communication satellites containing spherical tanks of liquid fuel. This communication satellite preliminary model appears to satisfy a significant number of earth phenomena, eg. energy production need, retardation of earth rotation, and westward drift of magnetic anomalies.

It is proposed here to continue the energy dissipation tests described in the referenced papers and to augment these with laser doppler and other measurements of internal flow velocities. A critical parameter is the ellipticity of the oblate spheroidal mantle-core boundary. Tests are needed using very precise spheres which can be compared with tests using spheroids having ellipticities of 1/400 and 1/25. Liquid and kinematic parameters will be varied to create theoretical Ekman boundary layers both less than and greater than the size variations due to ellipticity. Of particular interest will be the transition and early turbulence regions and their response to surface roughness. To complete the interaction of core dynamics with mantle

dynamics, it is proposed also to construct transparent elastic and semi-plastic thick walled spheres filled with liquid. These will be suspended in an immiscible liquid as a means of experimentally modelling an earth mantle-core system in zero gravity. This mantle-core model will be subjected to spinning, precessing, and other perturbing forces to examine experimentally oscillatory and "creep" phenomena in the core and in the mantle.

All three facilities have been constructed and are in various stages of operation at the Rotating Fluids Laboratory at UCSB under the direction of Dr. J.P. Vanyo. Experiments (some preliminary and as yet unpublished) have already been completed similar to those proposed above. Only a minimum of funds and effort will be required to begin obtaining useful results. A two year effort is proposed to explore carefully the phenomena.

RESEARCH PLAN

The Rotating Fluids Laboratory under the direction of Dr. J.P. Vanyo, includes three experimental facilities that provide capability for a major investigation of earth mantle-core mechanics. By operating these three facilities concurrently it will be possible to integrate the study of earth spin and precessional effects on mantle dynamics, on induced liquid motions in the core, on mantle-core interactions, and on precession as a possible major internal energy source.

Facility# 1

Measurement of liquid energy dissipation in liquid filled spinning and precessing rigid spheroidal cavities. Tests and analyses have been conducted since 1967 by Dr. Vanyo with application especially to communication satellite attitude stability²⁻¹¹. Recent analyses and tests have extended the research to the geophysical earth core problem¹. Preliminary tests using oblate spheroidal cavities with ellipticities of 1/25 and 1/400 have been initiated but not yet reported. Use of scaling laws developed to extrapolate accurately between laboratory and communication satellite scale precessing fuel tanks have been analyzed relative to earth scale mantle-core boundary phenomena. This work will continue and may provide direct experimental evidence for understanding more fully the earth's interior and a major source of energy for movement within it.

The energy dissipation test facility is available for use. It is in perfect condition and is being used at present as part of a UCSB contract with an aerospace manufacturer to test and to help improve design of communication satellite reaction control fuel tanks with Dr. Lanyo as principal investigator. An oblate spheroidal tank machined from 6061-T6 aluminum alloy and with an ellipticity of 1/400 has been fabricated using Departmental funds. Preliminary tests have been completed.

Funds are needed to fabricate similar tanks, one with an ellipticity of 1/25, and one spherical. A cast epoxy tank with ellipticity of 1/25 was fabricated earlier but it disintegrated at the necessary speeds for scaling earth interior mechanics, as did an earlier cast epoxy spherical tank.

Facility #2

Measurement of liquid flow velocities in liquid filled spinning and precessing spheroidal cavities. This experiment has been in the design construction, and development stage for several years. Because of needs unique to the energy dissipation apparatus (above) it is impossible to use that equipment to see and/or measure flow velocities. This second experimental apparatus is nearly completed. It will enable measurement and recording of flow velocities using photographic, laser doppler and other flow measurement techniques. The apparatus spins and precesses a tank at the exact same parameters as the energy dissipation apparatus so that flow velocity measurements can be correlated directly with energy dissipation measurements. It is anticipated that this will develop into a unique and important method for the detail study of transition and turbulence in rotating flows. Used concurrently the two facilities will provide an experimental method for assessing liquid motions and energy rates in geophysical models of the earth's liquid core and of mantle-core boundary interactions.

This major experimental facility has been developed using Departmental funds with about 5% (\$2000) assistance from a current NASA grant. About 15% additional funds for a specialized tank and special instrumentation is needed to apply this experimental facility to the specific needs of the proposed geophysical research.

Facility #3 Observation and measurement of oscillations of elastic and semiplastic thick walled spheroidal shells filled with liquid and

subject to rotational and translational perturbations. Tests and analyses for this research have been funded to date by two "seed money" NASA grants administered through the University Affairs Office at NASA Ames. The purpose of the research was to develop capability for earth laboratory experiments to simulate the dynamic behavior of liquid drops in simulated zero-gravity and ultimately to investigate similar phenomena in the space shuttle orbital environment.

The laboratory experiments make use of a setup to suspend a drop of one liquid in a second immiscible liquid, both having the same density. The suspended drop can then be oscillated and/or rotated to compare actual and predicted behavior. The original such experiments were performed by Plateau in the middle 1800's and are reported in Smithsonian Reports¹². More recent studies of liquid drop behavior in simulated zero and near zero-g conditions have yielded improved accuracy and analytical methods and have pursued various related phenomena.

The emphasis of the UCSB research has been on studies of compound drops, i.e., a drop within a drop. One line of research has developed sets of more than two immiscible liquid systems along with elastic and semi-plastic spheroidal envelopes containing an interior spheroidal liquid core. Another line of research has developed a rotating tank system that contains remote manipulators for injecting and withdrawing compound liquid drops, for suspending and rotating the drops, and for observing the resulting phenomena. A critical need, corrected only recently, has been for an adequately large, precise, and controllable spin table as a test fixture for the rotating tank system. Facility #2, described above, includes a spin table with capacity for the existing tank system, and it also has additional capacity for later improvements.

Experiments are planned in which a model earth mantle-core system is subjected to spin and precessional motions. Steady state interactions between the mantle and core will be studied, followed by observations and analysis of responses to perturbing forces and moments. Needs specific to this experiment include funds for fabricating a series of elastic and semi-plastic thick walled spheroidal shell models and for additional instrumentation to measure and to record the resulting phenomena.

Schedule and Cost (Preliminary)

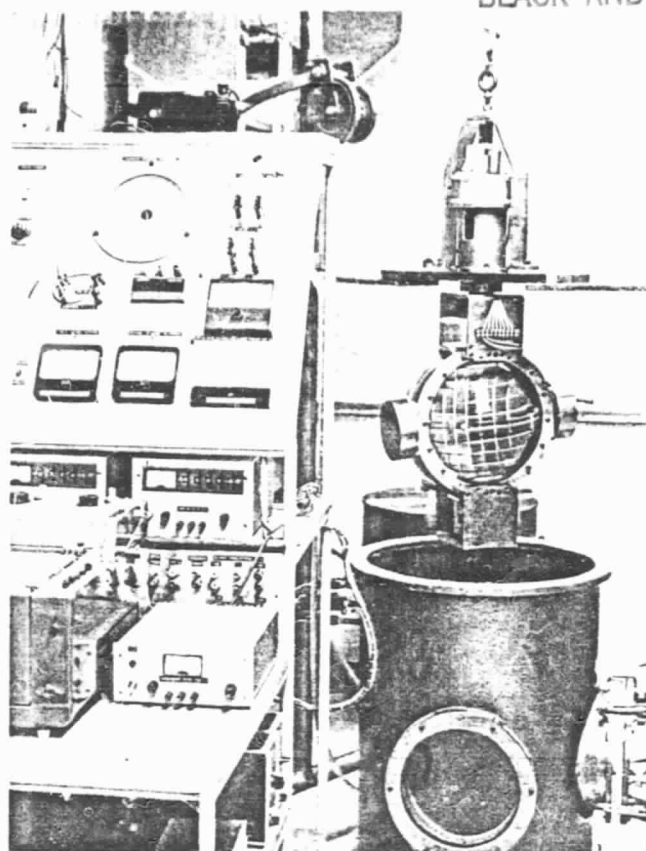
Note: Pages 5, 6, and 7 of this preliminary proposal were details of a tentative plan and preliminary cost estimates to accomplish a two-year research program. These schedules and costs are no longer relevant.

A formal proposal is now in preparation for a research program that uses the three facilities described here as laboratory support for a series of experiments to be performed in the space shuttle environment.

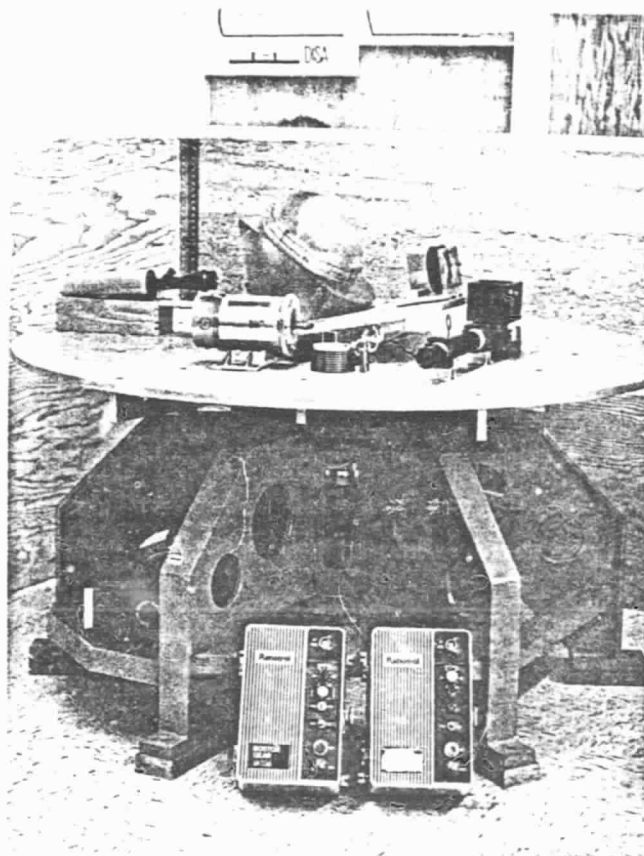
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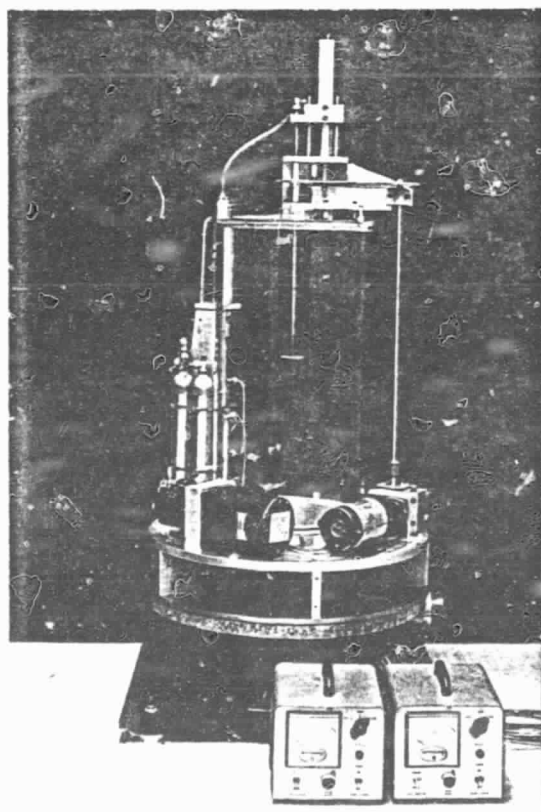
ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



Facility 1. Energy dissipation apparatus (left).
Cast epoxy 22 cm ID spherical tank with baffles is shown.



Facility 2. Flow velocity apparatus (above).
Main table is 5 ft dia. Tilting secondary table, partially assembled, is 2 ft dia.



Facility 3. Liquid buoyancy apparatus (left).
Tank is 12 inch dia, 22 inches high. Will be used on 5 ft dia table of Facility 2.